NONDESTRUCTIVE EVALUATION OF STRUCTURAL SILICONE ADHESIVE JOINTS IN BUILDING ENVELOPE SYSTEMS

by

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B.S. Civil Engineering
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Submitted to the Department of Civil and Environmental Engineering
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Abstract

Structural silicone glazing (SSG) systems are a popular curtain wall building envelope system of the 1990's. The systems evolved from the use of new materials and methods to produce increasingly functional yet aesthetically pleasing building enclosures. SSG systems are used generally for cladding systems where a continuous glass wall effect is desired on the exterior of a building with no visually detectable support or framing. A lack of complete knowledge of these systems makes them prone to structural failures as well as other deficiencies like energy inefficiency. Financial burdens derived from deficient envelope systems are quite significant. This work proposes a diagnostics program for continuous nondestructive evaluation of structural silicone glazing system seals. These structural seals are the most important component of structural sealant glazing systems. An innovative application of polyvinyl fluoride film (PVDF) sensors in ultrasonic testing is explored for the purpose of turning functionally mediocre building envelope systems into high performance building components. These systems should maximize use of building systems by optimizing the use of construction materials, HVAC systems, and other building systems and components. The proposed methodology may be integrated in common day building automation systems (BAS). Models of SSG systems were constructed and tested to determine the potential of the ultrasonic monitoring system. The results indicate there is promise in the method. Further research opportunities are abundant in this particular application of nondestructive evaluation methods.

Thesis Supervisor: Jerome Connor
Title: Professor of Civil and Environmental Engineering

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CHAPTER 1

OBJECTIVE AND METHODOLOGY

1.1 Introduction

Current advances in structural and material technology have created countless opportunities for innovation in the design of buildings. Over the past few decades, engineers have utilized advancements in science to create taller, more flexible, and adaptive main structural frames. Architects have applied scientific advancements to their continual efforts to invent new methods of enclosure which are functional yet aesthetically pleasing. A combination of efforts from the architectural and structural teams yields building envelope systems. The building envelope system is defined as "a building enclosure, extrinsic to the [main] frame, which provides the skin of the building-to protect the interior from the outside elements and to provide the most important visual component of the building exterior".[1]

Utilization of new material and methods also introduces slight disadvantages. Due to the newness of materials and techniques in building design, documented history of the material behavior may not be available. A solution to the dilemma of insufficient knowledge of failure mechanisms is to provide nondestructive continuous monitoring for the innovative components of the design during and after construction. If eminent failure is not an issue, this solution provides a way for new designs to be implemented, with diagnostic capabilities for assessment of the design's integrity. These diagnostic capabilities need not be limited to assessment of new systems, they may also be used on older systems to provide quantitative measures of building conditions integrity and performance.

This thesis identifies and discusses issues pertinent to high performance of building envelope systems; common failures in building envelope systems; new materials for innovative envelopes; and more importantly, proposes a methodology for continuous monitoring and diagnostic capability for a crucial component of Structural Silicone Glazing (SSG) Systems. The structural silicone glazing system, an option for building envelope systems, was selected for focus due to its current popularity. SSG systems are used widely for cladding systems where a continuous glass wall effect is desired on the exterior of a building with no visually detectable support or framing.

Research conducted for this thesis involves preliminary design, simulation, testing, analysis, and recommendations of a nondestructive testing application for evaluation of a key building envelope system component. The goal of the proposed technique is to characterize the integrity of structural silicone glazing system silicone seals. These seals are a critical structural element in many of today's most modern and impressive building envelope glazing systems.

CHAPTER 2

BUILDING ENVELOPE SYSTEMS

2.1 The Evolution of Building Envelope Systems

As mentioned before, building envelope systems provide the "skin of the building". Roofing systems are considered an element of the entire envelope system. This thesis, however, focuses mainly on the exterior wall system.

Pre-industrial age buildings were normally constructed with massive load bearing walls which served as both the structure and thermal barrier of the building envelope system. The massive walls stored heat during the day and radiated that heat through the building on cold nights. On hot days, the walls provided shade and tempered the interior temperature from hot external climates. Nineteenth century development of cast-iron and steel frame structures, followed by reinforced concrete frame structures, signaled the end of prevailing massive load bearing systems. Engineers and architects began to invent new methods of enclosure. Steel and concrete frames were able to provide structure to deal with gravity and lateral loads of unprecedented heights. Building enclosures, extrinsic to the main structure of the frame, could be designed to protect building interiors and provide building users with an abundance of light and great views. Such concepts were unheard of with massive load bearing wall buildings. Through emerging technology, facades with the option for expansive glazing in the system, or cladding, was born. [1]

Building types, materials, and construction methods emerged at an accelerated rate in the twentieth century. Unfortunately, the materials and methods were not thoroughly understood. As a result, codes, regulations, and standard tests that replaced the empirical methods craft-persons used in the old methods were deficient in complete design and construction of buildings. The innovation came with a lack of competence in engineering buildings. Failure of many building envelopes can be traced to the general lack of emphasis in detailing design decisions which affect the ultimate performance of a building system.

2.2 Building Envelope Components

Building envelope components generally consist of six basic components: the exterior material, support framing, interior finish, insulation, joint treatment, and internal drainage. Some cladding systems integrate all components into one package. Such systems include metal and glass curtain walls. Other cladding systems require selection and specification of each component separately.

The function of support framing will be discussed later in this thesis. The interior finish on cladding is an architectural treatment applied to the interior face of the support framing or a separate wall. Energy conservation, mandated by codes and responsible engineers, have led major developments in insulation of building envelope systems. Insulation reduces energy costs and minimizes infiltration of unconditioned air into a building. Joints serve two primary purposes: they allow for ease of construction and compensate for movement in the building systems. Internal drainage is necessary so that no water is permitted to penetrate a building's exterior surface to damage the building interior. Mechanisms should also be provided to allow moisture within the wall to escape to the building exterior.

2.3 Building Envelope Systems

Current cladding systems are classified into three basic types dependent on their method of attachment to the structural frame. The three types are the attached, infill, and curtain wall systems. [1]

The attached system is directly attached to the main structural frame in large panels which span stories or bays. They are constructed on the frame with back-up material anchored to the slab, and the exterior finish covering the structural frame. An advantage to use of the attached system is the capability of the components to be fully insulated and protected from deteriorating effects of weather.

The infill system is installed between the exterior floor slab edges. Often this method is used to expose exterior columns of the main structural system. The primary advantage of this system is that it can be installed from the interior of the building without use of scaffolding. However, the structural frame is exposed to external elements, and the system is virtually impossible to insulate. Also, differential movement of the envelope and the main structural frame cause great maintenance problems.

Curtain wall systems are attached to the structural frame with angles or sub-framing. The most prevalent curtain wall systems are metal or metal and glass walls. These systems are used on many of today's skyscrapers. Curtain wall systems may also be constructed of natural stone, precast concrete, or other combinations of materials. Today, the curtain wall option is selected most often in enclosure systems and, therefore, is the focus of this thesis.

2.4 Curtain Wall Systems

Exterior walls of curtain wall systems are generally suspended from the main structural frame. Ideally, the wall system's dead weight and wind loads are transferred to the main structural frame through anchorage and fasteners between the skin and the mainframe. See Figure 2.1 for an illustration of these building components.

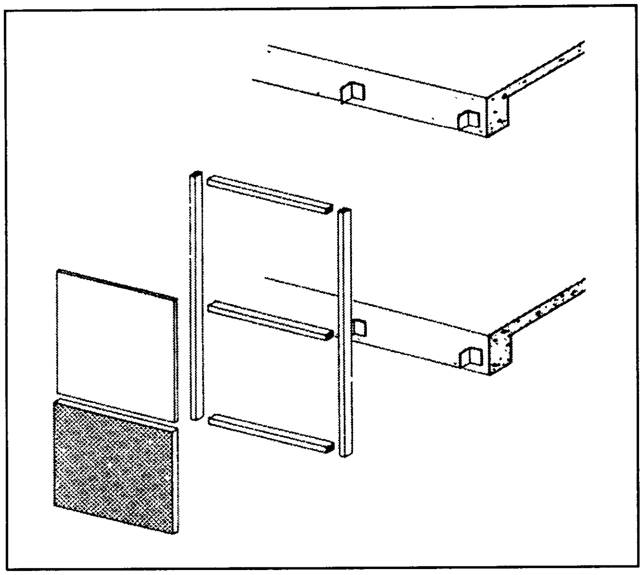

Figure 2.1 Illustration of building envelope frame components which are anchored to spandrel beams in the main structural frame of a building .

Joint design in exterior wall systems is crucial because it, along with properly designed fastening techniques, permits construction of continuous wall surfaces of any size creating the entire facade of the building, see Figure 2.2

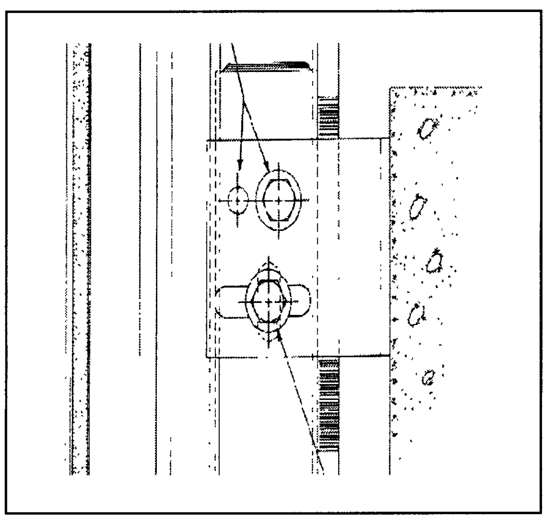

Figure 2.2 Connection detail of a vertical frame member, a mullion, anchored to spandrel beam of a structural frame.

Wall systems generally consist of a rectangular grid of vertical and horizontal members which form a framework, or frame. Prefabricated components are erected in the following process: first vertical members are mounted and aligned; then the horizontal members are fastened between them to form a grid; lastly, the frame openings are subsequently filled with space enclosing panel inserts or glazing (glass). See Figure 2.3 for a sketch and detail of a typical building exterior frame system. [2]

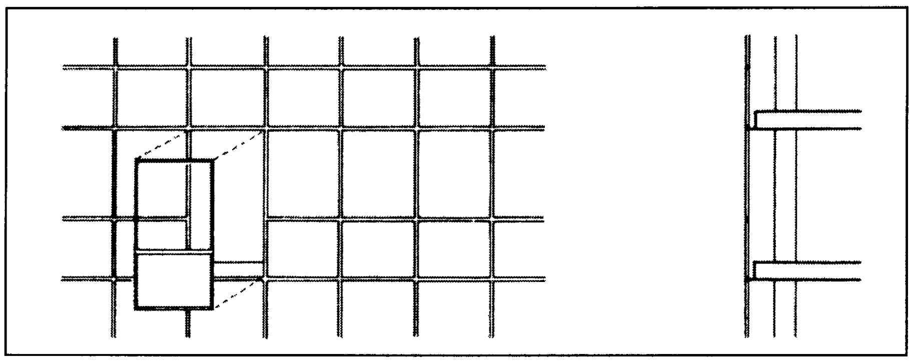

Figure 2.3 Sketch of typical structural frame system in building exterior walls.

2.5 Structural Sealant Glazing (SSG) Systems

Structural sealant glazing, one of many options for building envelope systems, is popular among designers who desire a multitude of aesthetic options. It allows installation of glass wall panels with no visible means of support or outdoor framing members. The result is a smooth, uncluttered appearance with relatively unobtrusive outdoor weather-seal joints between individual panels, or lites, of glass.

SSG systems are composed of horizontal and vertical framing members which provide a back-up surface to which glazing is adhesively bonded with structural sealant. Currently, structural sealant is uniquely made of silicone rubber. Silicone has been commercially available since 1950. It is still fairly new as regards construction materials.

Traditional rules of joint design do not apply to SSG systems. The bonding material serves as the main structural component in glazing-to-glazing and glazing-to-frame member joints in the exterior wall system. The sealant provides a weather-seal in addition to transferring loads from glazing to its perimeter support. Silicone sealant must be durable, reliable, and have sufficient adhesive strength to hold the glazing under imminent wind load stresses. Additionally, the seal should absorb thermal and differential settling stresses created in and between glass and metal frame members. Clearly, the sealant is a multi-functional component. See Figs. 2.4 and 2.5 for illustrations of the mullion/glazing bond.

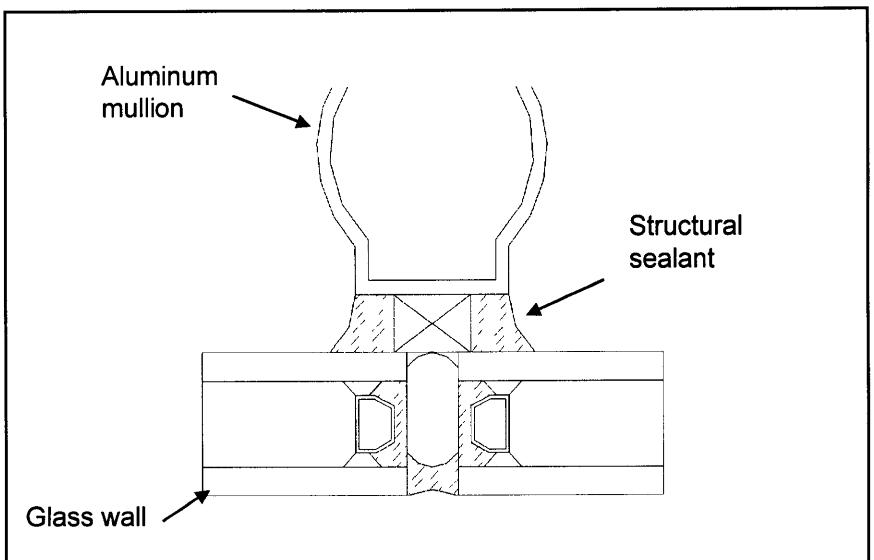

Figure 2.4 Silicone sealant bonded glazing to mullion detail.

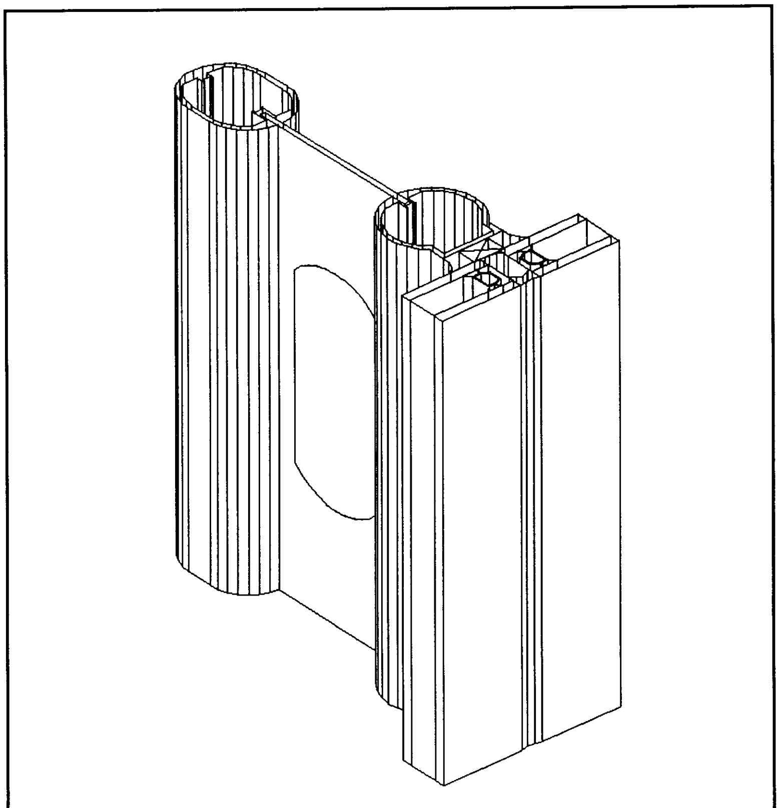

Figure 2.5 Three dimensional perspective of a silcione glazing system's mullion bonded to glazing detail.

2.6 Sealant / Adhesive Considerations

> *"Probably the most important component of structural sealant glazing systems is the sealant adhesive material".*
>
> *AAMA – Structural Sealant Glazing Systems Design Guide, 1985*

Long term structural integrity of SSG systems depends on proper structural sealant specifications; comprehensive system design; material integrity and compatibility; correct cleaning and application procedures; and continual and sufficient maintenance.

Structural capabilities of silicones involve two very important material properties: internal cohesive strength and adhesive or bond strength. Adhesion may be evaluated by observing the type of bond which the sealant develops to a substrate. In this case, the substrate are the metal framing members and glass panels of the cladding system. Two types of bond failures which occur are adhesive failures and cohesive failures. Adhesive failure is defined as a condition in which the sealant pulls cleanly away from the substrate leaving no material behind. In such situations, structural properties of the material are not fully used. Cohesive failure exists where the bond developed to a substrate exceeds the internal or structural strength of the material [3].

2.7 Sealant Failures

In order to extend the operative life of building exterior systems, cohesive and adhesive properties of structural silicone sealant must be maintained. History and research have provided opportunities for observation and documentation of common causes of sealant degradation and failure. Although this information does not pertain specifically to structural silicone sealant, it is valuable for predicting potential failure modes of the material. The causes of destruction include overstressing of sealant; movement during and after cure; undersized joints; sealant being applied over degraded substrate; lack of proper priming; sealant/substrate incompatibility; environmental degradation; weather deterioration; ultraviolet radiation; and heat, moisture, and ozone exposure.

Once a sealant has been subjected to a cause of failure, problems may be manifested in any of the following ways: debonding of seal from its substrate; crazing and cracking in the seal; hardening (reduced material elasticity); plasticity; and bubbling in material.

An array of overall building problems are caused by failed sealant. Building envelope issues derived from seal failure include: structural compromising of the envelope system components; interior or exterior building material developing damage due to water infiltration through an incompetent seal which spurs water induced mechanisms such as corrosion, decay, and freeze-thaw action; air infiltration causing drafts and whistling noises; loss of energy efficiency caused by leakage of heated or conditioned air; poor indoor air quality (IAQ) from microorganism growth in damp, concealed spaces; and damage to furniture, property, and interior finishes.

2.8 Building Envelope Summary

This chapter has established the need for maintenance of sound building envelope systems, in particular structural silicone glazing systems. Chapter 3 introduces the concept of nondestructive evaluation (NDE). This thesis claims that properly designed structural silicone glazing systems along with comprehensive nondestructive testing instrumentation should produce high performance building envelope systems from a structural, environmental, and aesthetic perspective.

CHAPTER 3

NONDESTRUCTIVE EVALUATION

3.1 The Present State of Structure Evaluation

Current methods of integrity assessment involve periodic applications of evaluation techniques, and in some cases only one application of a single evaluation method to ascertain the structural and material state of a building. Such infrequent appraisals undoubtedly result in material property degradation by failing to intercept safety critical problems or even minor problems that progressively deteriorate the facility. Resultant problems eventually require major finances to repair or maintain. A solution to this problem is to develop a "smart structure".

Smart structure entails development of a strategically designed sensor system to continuously monitor the soundness of a newly constructed or retrofitted facility. Nondestructive evaluation methodologies are used in building systems as a means to discern and quantify degradation of materials and structural components caused by destructive mechanical and chemical environments.

Design of structural systems should employ construction materials that can be equipped with in-situ sensors to facilitate nondestructive appraisal of material and structural properties. Thoughtful design of structure, along with comprehensive diagnostic systems, transforms mediocre facilities into high performance facilities from a building functionality perspective.

3.2 Condition Assessment Methodologies

Smart structures should provide ways to "see into" structural members. Imbedded defects in structural members, for example, voids, cracks, discontinuities, and delaminations, are detrimental to optimal performance. Contemporary sensing methods are being expanded to determine distress levels in building components. Methodologies are being developed to determine areas of a structure that are in danger of degradation. These development are known as known as Nondestructive Evaluation (NDE).

NDE can be used to assess much more than the aforementioned gross defects. NDE is also used for characterization of solids, their microstructure, texture, morphology, chemical constituents, physical and chemical properties, and methods of preparation. The following paragraphs list three widely used NDE methods and examples of their use.

Radiography uses electromagnetic energy to check changes in material density and variations, and placement of internal parts. It can be used to inspect a wide range of materials thicknesses, is versatile, and films resulting from radiography provide a record of the inspection. Examples of its use include evaluation of pipeline welds for penetration, inclusions, and voids, and testing for internal defects in castings.

Magnetic particle inspections (MPI) entail observing of leakage of magnetic flux caused by surface or near-surface cracks, voids, inclusions, material, or geometry changes. It is inexpensive or moderately priced, and sensitive to both surface and near surface flaws. Unfortunately, magnetic particle inspection is limited to ferromagnetic materials. Also, extensive surface preparation and post-inspection demagnetization may be required. Applications of MPI include evaluation of railroad wheels and large castings for cracks.

Ultrasonic methods are probably the most researched methodology of the three highlighted. The technique uses changes in acoustic reflections, impedance, frequency, attenuation, and time of flight to assess material density, inclusions, cracks, delaminations, thicknesses and other characteristics. More on this technique follows.

3.3 Ultrasonic Testing

This thesis proposes the ultrasonic technique for assessment of structural sealants in building envelope systems. Some advantages to ultrasonic testing include (1) high sensitivity which aids detection of minute discontinuities, (2) good penetrating power, (3) accuracy in measurement, and (4) fast response permitting rapid and automated testing.

When a sonic disturbance occurs at one end of a solid, it travels through the solid in a finite time as the sound wave vibrates molecules, atoms, and particles present. Sound travels with velocities dependent on the mechanical properties of the medium. Imperfections and inclusions in solids cause sound waves to be scattered, resulting in echoes, reverberations, and a general dampening of the sound wave. Audible sound corresponds to the range of frequencies of approximately 20 to 20,000 Hertz (Hz), or cycles per second. Ultrasound is a term used to describe mechanical vibration waves above the audible range. Sounds travel at different velocities through different media, and its velocity varies very little with frequency in most metals. The range of frequencies used in ultrasonic testing is from less than 0.1 to greater than 15 MHz, and typical values of wavelengths in ultrasonic testing are from 1 to 10 mm. [4]

3.4 Transmission and Reflection Techniques

Ultrasonic testing is generally performed using either of two techniques: the through-transmission or pulse-echo methods. A beam of ultrasonic energy is directed into a test object and either the energy transmitted through the object is measured (the through-transmission technique), or energy reflected from discontinuities in the object is measured (the pulse-echo technique). Collected information is useful because an ultrasonic beam travels with little loss through homogeneous material. Energy loss only occurs when the ultrasonic beam is intercepted and reflected by grain boundaries or discontinuities in the elastic continuum.

3.4.1 The Through-Transmission Technique

Using the through transmission technique, a test object is insonified (filled with sound waves) by coupling an ultrasound transmitter to one surface of the specimen. Instruments used to transmit and receive ultrasonic energy are a form of piezoelectric transducers. The transmitting transducer vibrates particles in the coupled material. This incites wave propagation through the medium. A receiving transducer is coupled on a surface directly opposite the transmitting transducer in the path of the wave. If no obstructions are encountered during the wave's journey through the medium, the sound energy arrives at the other surface with essentially the same magnitude of energy the incident wave possessed. However, if the material contains a discontinuity, full power of the wave is impeded. This results in reduction of the energy amplitude measured at the receiving transducer and is called attenuation. Refer to figure 3.1 for a schematic of the through transmission technique.

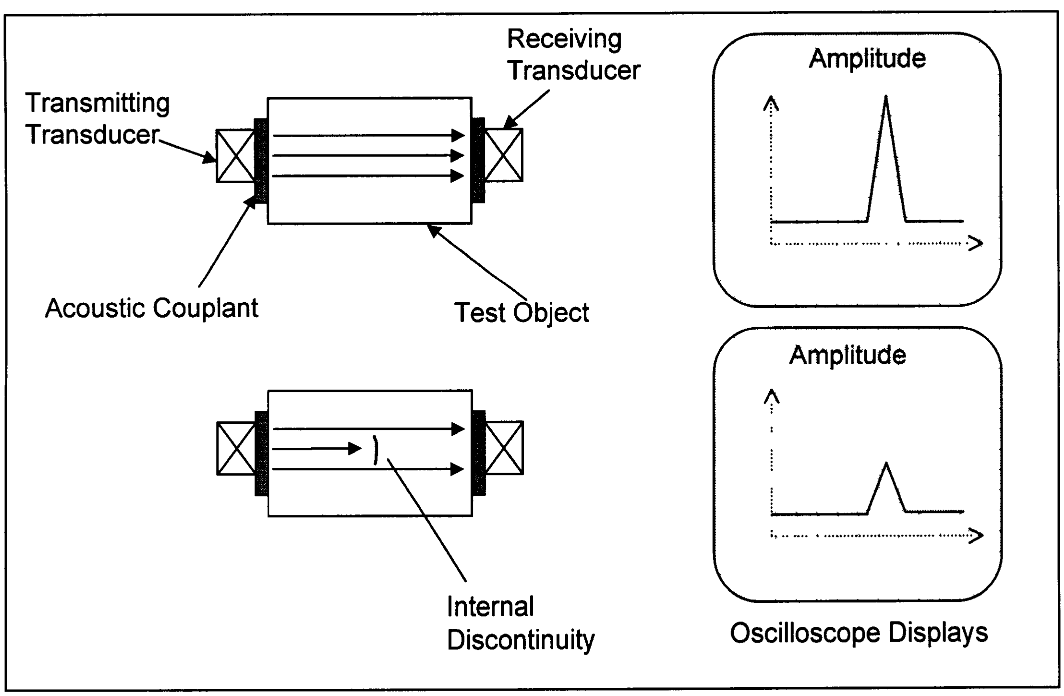

Figure 3.1 An illustration of through transmission principles.

3.4.2 The Pulse Echo Technique

The pulse echo technique involves the same instruments found in the through transmission setup. However, this technique uses one transducer to both emit and receive ultrasonic energy. A transducer is coupled to the specimen surface sending a pulse of ultrasonic energy through the medium. The pulse is reflected by any discontinuities or major interfaces encountered while traversing the material. Reflected pulses are detected by the transmitting transducer. Results plotted on an oscilloscope trace present data in amplitude vs. time yielding rich information. Reflections showing reductions in amplitude of the incident pulse as well as unanticipated reflections in the signal indicate scattering caused by internal flaws or discontinuities. Additionally, time-of-flight data obtained from measures of time lapse between reflections combined with the velocity of sound waves through the specimen's material type can be used to calculate material thickness and depths of discontinuities in the specimen. See Figure 3.2 for diagrams of the pulse echo technique.

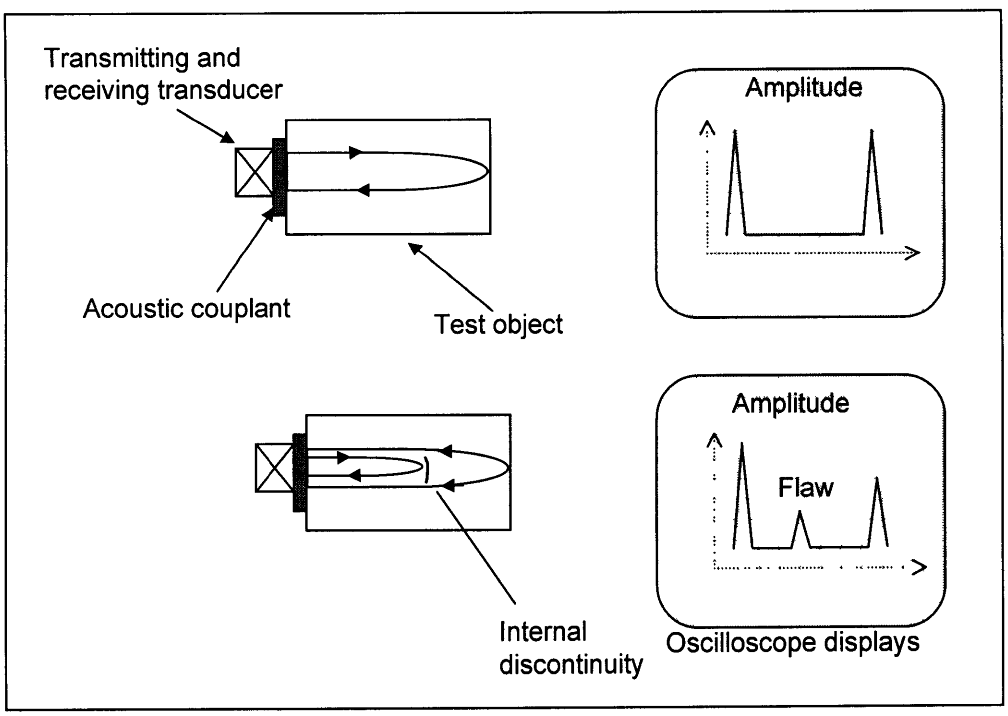

Figure 3.2 Illustrations on the pulse echo technique.

3.5 Ultrasonic Material Characterization

Ultrasound may also be used for material characterization. The pulse echo technique is used for this purpose. Measurements of ultrasonic velocity and attenuation are bases for evaluating elastic modulus, characterizing microstructure, and for assessing mechanical properties. For velocity measurements, the objective is to establish the exact time interval needed for a signal to travel between the front and back surfaces of a test object. Signal analysis yields the group velocities and phase velocities, the velocity dispersion characteristics of the tested material.

The objective of attenuation measurements is to determine the energy loss experienced by signals that traverse a test object. Signal analysis yields the attenuation coefficient as a function of frequency. That attenuation value is unique to material properties. A correlation between the frequency dependent attenuation and material properties yields information like gross particulate size and micro-structural qualities of the tested medium. Signal analysis can be done in either the time or frequency domain. However, the data needed for material characterization will be deficient unless experiments are conducted with broad band phase velocity and attenuation spectrum analysis.

3.6 Ultrasonic Wave Equations

A pulse echo technique scheme is simulated again in Figure 3.3 for purposes of presenting variables, equations and the physical phenomena represented by these variables to quantify velocity and attenuation. The equations in this chapter are from the Nondestructive Testing Handbook Second Edition, Volume 7 – Ultrasonic Testing. [4]

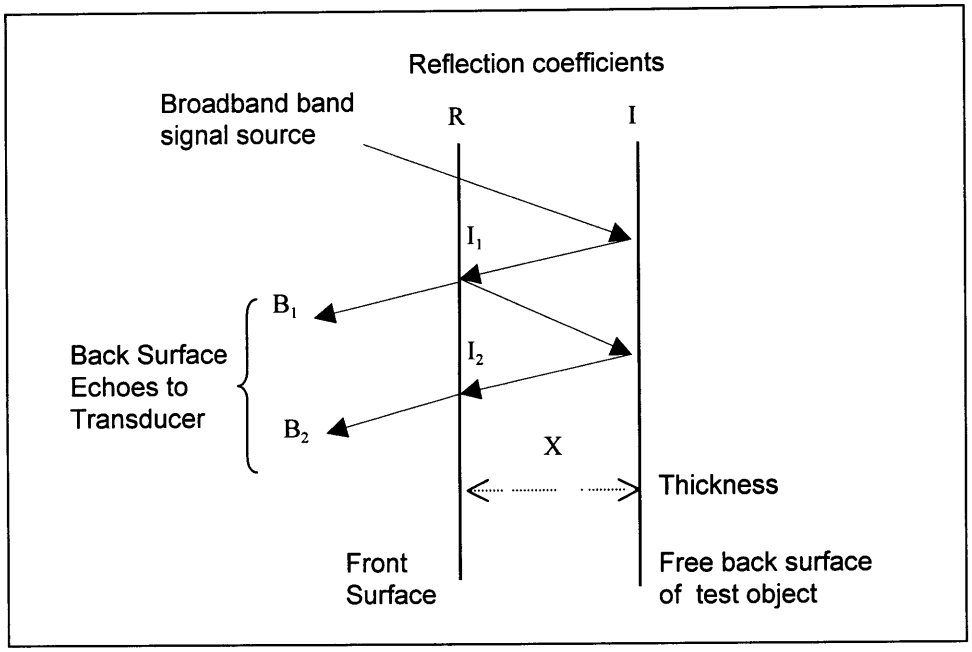

Figure 3.3 Diagram of an pulse-echo system for determining the frequency dependence of velocity and attenuation.

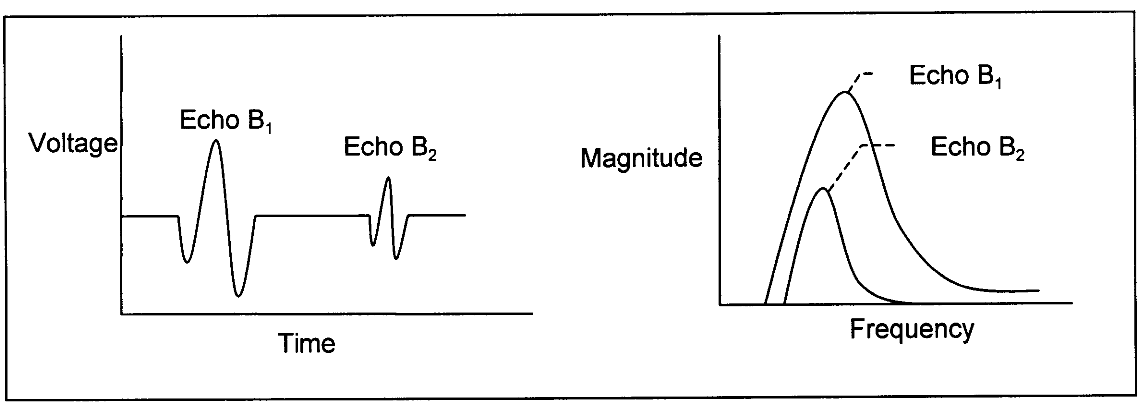

Figure 3.4 Sample signal trace and frequency response curves.

Attenuation Equations

Refer to the first two echoes, B_1 and B_2, of the signal in Figure 3.4. The cross correlation or group velocity is given by:

$$v = \frac{2X}{\tau_o} \qquad [3.1]$$

where:

X = the test object thickness (meters); and

τ = the time shift (seconds).

The value of τ in Eqn 3.1 is $-\infty \le \tau \le \infty$ and is determined the maximum value of Eqn. 3.2

$$\left| \int_{-\infty}^{+\infty} B_1(t) B_2(t-\tau) dt \right| \qquad [3.2]$$

The phase velocity is given by:

$$v(f) = \frac{4X\pi f}{\Delta B} \qquad [3.3]$$

and

$$\Delta B = B_2 - B_1 \qquad [3.4]$$

$$B_1(f) = \tan^{-1} \frac{I_m[B_1(f)]}{R_e[B_1(f)]} \qquad [3.5]$$

and

$$B_2(f) = \tan^{-1} \frac{I_m[B_2(f)]}{R_e[B_2(f)]} \qquad [3.6]$$

where:

f = frequency (Hertz);

I_m = imaginary number; and

R_e = real number.

The quantities B_1 , B_2 , I_1 , I_2 and R in Figure 3.3 are functions of frequency; they are fourier transforms of corresponding time domain quantities. The quantities B_1 , B_2 , I_1, and I_2 are spectra of corresponding waveforms. The reflection coefficient of the front surface R is normally also a function of frequency. Interfaces in materials have a finite thickness that generally exceeds the transmitted wave's wavelength. In this case, transmission and reflection coefficients are frequency dependent because the interface will interact with the wave. The general equation for the reflection coefficient as a function of frequency is:

$$|R(f)| = \left| \frac{F_2(f)}{F_1(f)} \right| \qquad [3.7]$$

where the Fourier spectra of echoes from the end of the buffer are $F_1(f)$ and $F_2(f)$, with and without coupling to the test object, respectively.

The reflection coefficient is unity at the free back surface of the test object. A reflection coefficient of unity indicates complete reflection, no through transmission. Internal echo I_1 is the source of the signal B_1, as shown in Figure 3.3 A part of the energy of I_1 is reflected and appears as the second internal echo I_2 causing a reduced amplitude echo B_2. Therefore:

$$B_1 = G(1-R)I_1 \qquad [3.8]$$

$$B_2 = GTR(1-R)I_1 \qquad [3.9]$$

The quantity T represents a transfer function of the material defined in terms of the attenuation on a pulse which has traveled twice through the test object of thickness X:

$$T = \exp(-2X\alpha) \qquad [3.10]$$

where α is the attenuation coefficient. Like R, T, G, B_1 and B_2, α is a function of frequency. Attenuation coefficient vs. Frequency plots are termed attenuation spectra. G is a combination of transfer functions related to the signal acquisition system. In the pulse echo technique, G drops out the attenuation coefficient equation. The attenuation equation may be written as:

$$\alpha = \frac{1}{2X}\ln\left(R\frac{B_1}{B_2}\right) \qquad [3.11]$$

Velocity Equations

Elastic moduli of a test material may be measured directly from longitudinal (v_l) and shear (v_s) wave velocities of ultrasound. The following equations are reasonable estimations of mechanical properties only if the test objects' dimensions are much greater than the wavelength of ultrasound.

$$L = \rho v_\ell^{\,2} \qquad [3.12]$$

$$S = \rho v_t^2 \qquad [3.13]$$

where:

v_l = longitudinal velocity (meters per second)

v_t = tranverse velocity (meters per second)

L = longitudinal elastic modulus

S = shear elastic modulus.

Other elastic constants include:

Bulk modulus = $L - (4/3)S$

Young's modulus = $(3L - 4S) /(L - S)$

Lame's constant = $(L - 2S) / 2(L - S)$

Nonlinear material elasticity and porosity significantly complicate these simple equations of attenuation and velocity measurements. Velocity becomes related to porosity factors, grain size, shape, and orientation factors particular to the given material. For most porous materials, velocity is found to be an increasing function of density. Mechanical strength and fracture behavior of some materials have an important and complicated dependence on porosity, impurities, and grain structure as well. Therefore, the use of nondestructive ultrasonic evaluation methods is justified for quantifying such properties. Although exact theoretical formulations may not be available for precise quantification of all desirable properties under all conditions, the empirical and theoretical formulations established thus far have served well as predictors of material properties.

The pulse echo method is the preferred method for measurements of attenuation and velocity spectra. It is currently the most used method for quantitative characterization and assessment of material properties. Ultrasonic wave properties are affected by the conditions of bulk microstructures, interfaces, bonds, substrates, coatings and similar factors that govern material response and integrity. Information presented in this chapter prove ultrasonic testing to be an ideal candidate for evaluation of structural components of building envelope systems. The possibility is further investigated in Chapter 4 of this thesis.

CHAPTER 4

AN ULTRASONIC TESTING SCHEME FOR STRUCTURAL SILICONE GLAZING SYSTEMS

4.1 Standard Tests Performed on Cladding Systems

Testing programs for cladding systems have been developed and are currently used. They consist of at least the first two of the following three phases: 1) pre-construction testing, 2) quality control testing during construction, and 3) very limited post-construction testing. [1]

Pre-construction testing is conducted to verify that specific materials and components being proposed by the selected designers are in accordance with project specifications. Once cladding is in place, repair can be extremely expensive and very difficult, sometimes impossible. It is unwise to assume that all proposed materials and components, particularly critical ones, will perform according to specifications. Pre-construction testing consists of testing materials and sample areas of cladding mock-ups prior to general construction of the envelope system. Mock-ups of building cladding often reveal problems caused by unanticipated construction anomalies or tolerance variations of the structural frame the cladding encloses. Areas of common concern in testing the mock ups include: structural adequacy of cladding systems under wind load, effectiveness of the cladding system in controlling water penetration, and the ability of the cladding system to resist air leakage, condensation, overall thermal transmission, and seismic loads.

Quality control testing during construction is performed to confirm that the quality of the materials and components approved by pre-construction testing are maintaining acceptability during the course of construction. Basically the same tests used to justify the use of the materials in the system are used to verify that they are performing satisfactorily.

Post construction or in-place performance tests are relatively expensive. However, they have a positive effect on the quality of the design and construction techniques. Besides providing useful information about the quality of the building envelope, they motivate the construction crews to deliver desired workmanship since the tests are performed at unspecified times in unspecified locations of the envelope. During in-place tests, water penetration and air infiltration tests are most frequently performed because these are most likely to indicate regions of the envelope that fail to meet specifications. They are also the most economical to perform as compared to most other tests.

So far, this thesis has presented a comprehensive introduction to building envelope systems and the ultrasonic nondestructive evaluation methodology. Its goal is to integrate the building skin with a testing technique that will produce an aesthetically pleasing building envelope system equipped with an automated, comprehensive, continuously monitoring system. An extensive literature review performed in 1998, has not yielded evidence of such a proposal or system before.

Failure or deterioration of structural silcone seals in a structural sealant glazed system is a contributing factor to damage of the exterior wall system, air and water infiltration through portions of the system, and basic loss of energy efficiency due to losses through the deficient wall system. Continual detection and notification of structurally or materially unsound seals will significantly decrease the quantity and importance of problems related to defective envelope systems.

4.2 The Proposed System

A pioneering design approach is hereby presented. It involves using ultrasonic sensors to detect and monitor stress levels and deterioration in silicone seals. PVDF sensors, made from a piezo-polymer film, would be permanently affixed to the structural seals of a SSG envelope system. The sensor would continually sense the seal's condition by monitoring characteristics of ultrasound propagating through them. Prior correlations of ultrasonic parameters with sealant conditions may be used to analyze the data. Constant condition monitoring throughout the operational life of the structural seal is necessary to evaluate its efficiency. Monitoring also aids understanding of the principles which govern reliability of a particular design or construction procedure. Therefore, the monitoring scheme has two advantages; (1) it aids interception of potential structural and environmental problems in the building, and (2) it provides a tool through which performance of designs may be evaluated and modified in order to extend the service life of building envelope components.

This chapter reports several investigations of monitoring schemes performed on mock-up structural silicone glazing sealant conditions. Innovative and conventional sensors were used with pulse-echo techniques to identify stress states, voids, porosity, and inclusions in SSG sealant.

4.3 Why Polyvinylidene Fluoride (PVDF) Transducers/Sensors?

Ultrasonic waves are generated by transducers, in which a single electrical "spike" of short rise time is converted into high frequency mechanical vibrations within a solid. These mechanics are made possible by an active element made of piezoelectric materials. The selection of a transducer depends on the properties of the specimen to be tested. Ultrasonics of high frequency can give rise to good resolution enabling one to receive separate echoes from closely spaced defects. Deep penetrating power is also desirable, however this is most often achieved by lower frequencies.

There are several rationales for selection of a piezo-polymer film transducer in this proposed evaluation system. The polymer, specifically PVDF, is less expensive, thinner, and more light weight than piezo-ceramics. See Figure 4.1 for an illustration of a PVDF sensor. Piezoceramic sensors made of quartz or a ferroelectric polycrystalline ceramic would be the other option of a transducer for ultrasonic testing . However, PVDF's piezoelectric voltage coefficient is about 20 - 40 times larger than most commercially available piezoceramic materials. Since many transducers or sensors would be needed to permanently instrument an SSG envelope system, testing sensitivity and low price are a desirable feature.

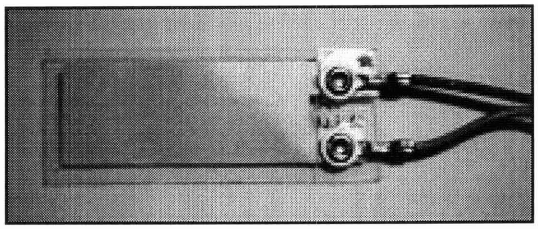

Figure 4.1 A PVDF sensor with leads.

Another advantage to the use of PVDF sensors is that they can be extruded into flexible films as thin as 9 micrometers. They are easy to shape, and the membranes can be attached to just about any substrate without disturbing its motion [5]. Therefore, the structural effect of mounting these films on operable building envelope seals should be negligible. PVDF sensors mounted flexibly on a seal would be very sensitive to the motion of the seal. When subjected to compressive or tensile stresses induced by the sealant's movements, the PVDF will emit a voltage which can be used to monitor sealant stress and strain levels.

PVDF transducers are not suited solely for dynamic events. The sensor also induces sound in objects coupled to it when subjected to a voltage. When a voltage is applied across opposing film surfaces, the film changes its net volume and temporarily redistributes its bulk charge. If the PVDF is properly bonded or coupled to a building seal, its change in volume of particles applies a pressure to the coupled material and sound is produced in the seal. Another way of stating this phenomena is to say the seal is "insonified". The production of sound in the seal yields a world of possibilities for testing.

PVDF sensors have been used previously in the research of adhesive joint monitoring techniques in the early 1990's.[6] Gregory L. Anderson of Thiokol

Corporation employed PVDF films to ultrasonically monitor adhesive cure monitoring and void/porosity content. Cyclic bond-normal stresses were quantified by imbedding film sensors in the adhesive bondline of polyurethane bonded plexiglas sheets and measuring the electrical voltages produced in the sensors by the stresses. Elastomeric butt joint bonds were also investigated for bond-normal stresses. These activities inspired the author of this thesis with an idea for application of the technology to critical components of building envelope systems. The capabilities of PVDF appear ideal for testing of SSG seals. Three sections of this thesis disclose experiments in and exploration of:

- testing of stresses applied to SSG system silicone seals (section 4.5)
- testing of structural silicone adhesive bond integrity (section 4.6)
- testing of diffuse discontinuities in structural silicone sealant (section 4.7).

4.4 Fabrication of A PVDF Sensor

Before discussion of the experiments, some attention will be paid to methods of fabrication of a PDVF sensor. Scientists first discovered piezoelectric activity in polyvinyl fluoride (PVDF) film in 1969. For the next 15 years, the material remained a laboratory curiousity [5]. In the last decade researchers learned how to mass produce many PVDF devices, and have collected much knowledge in application of the material. The film is generally used to sense motion by using tiny strips of the material prepared for measurement purposes.

Preparation of PVDF for motion measurement is as follows [6]. The film is commercially available from AMP Incorporated located in Valley Forge, Pennsylvania. It is uniaxially stretched to a draw ratio of about four. Then a 200 – 400 Angstrom layer of copper-nickel is vapor deposited on both surfaces of the film. The film is then piezoelectrically poled by subjecting it to a high electrical field across the film thickness at elevated temperatures. The film is piezoelectrically active in those regions where the metal alloy is left on both surfaces of the film. Electrical activity in the film are achieved by soldering electrical leads to positive electrodes of the piezoelectric elements. After complete assembly of the transducer, it is characterized and calibrated to meet performance characteristics.

Although some of the tests conducted in this experiment used a commercial ceramic transducer, the possibilities of PVDF sensors should surpass that of commercially available ceramic sensors. Unfortunately, more research and development of PVDF sensors was necessary before they could be used reliably for all tests performed for this thesis concerning building skin evaluation. Time and resource constraints prohibited full development of PVDF sensors for two of the tests conducted for this thesis. A commerical transducer was used instead. Research opportunities are plentiful in the area of PVDF sensor development.

4.5 Testing of Stresses Applied to Silicone Sealant in SSG Systems

Design of a SSG system specifies that standard exterior glass lites be structurally adhered to metal structural mullions, preferably ones made of aluminum. Recall Figure 2.4 for a detail of the connection. In a properly designed structural joint, the sealant absorbs all stress imposed upon the glass caused by the wind and thermal movement. Thermal movement occurs when the glass expands and contracts due to cyclical hot and cold temperatures. See Figure 4.2 for an illustration of the strains and stresses developed in the seal of SSG systems when subjected to wind loads.

Tensile adhesion, the force required to destroy the sealant, must never be applied to the seal during the service life of the building. Industry standards don't always subscribe stringent specifications that ensure comprehensive designs. The cost of a potential failure is too high to assume the silicone will offer long term performance stability required under *all* service conditions. A solution to the dilemma of assuring sealant stress conditions are not exceeding design strengths is to continuously monitor the undergoing stress values.

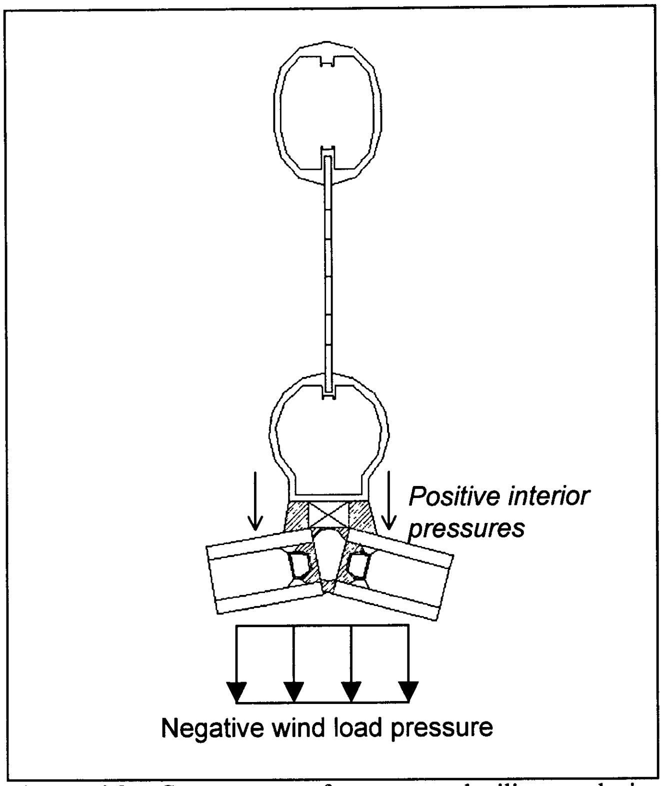

Figure 4.2 Components of a structural silicone glazing system subjected to wind loads. Note the bowing glazing and strained sealant.

A methodology to monitor stress conditions induced in the seal is hereby presented. As stated before, PVDF is sensitive to dynamic events. The proposition is to bond a small sized PVDF film sensor to a working structural seal. See figure 4.3 for locations. If the sensor/sealant bond is unbroken, stresses induced in the seal substrate caused by wind and thermal loads should also be experienced by the flexibly bonded PVDF film as well.

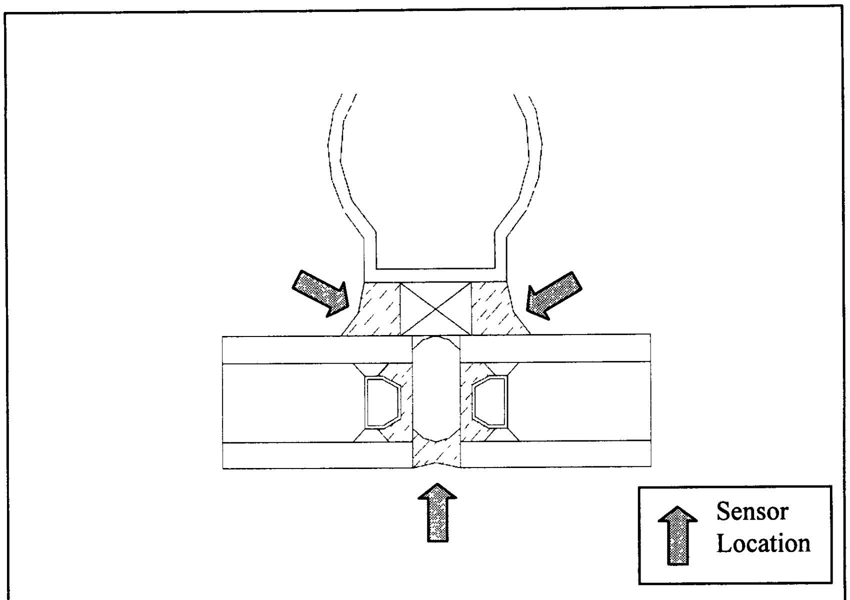

Figure 4.3 Proposed sensor locations on envelope structural seals.

Stresses in the film produce bulk voltages directly proportional to experienced stresses. Voltages can be calibrated with stresses to provide a reference for stresses values experienced by the PVDF sensor. The idea presents a prime opportunity to evaluate stresses within the seal and was explored in the following detailed experiment Leads are attached to the film and connected to a data aquisition system. Subsequently, data aquired could be conveyed to some central data recording and reporting system, perhaps a building automation system (BAS). This notion is further addressed in Chapter 5.

4.5.1 Conducted Stress Level Experiment and Results

A series of experiments were conducted for research for this thesis. All experiments used the same basic setup. Transducers and specimens were the only items switched during the tests. All tests were conducted using the ultrasound technique. Instruments used included: two broadband PVDF transducers, a Panametrics model 5072PR pulser receiver unit, a Textronics TDS210 digital realtime oscilloscope, a Panametrics 5.0 MHz contact transducer, a data aquisition program, and several BNC cables and connectors. Refer to figure 4.4 for an illustration of the set-up.

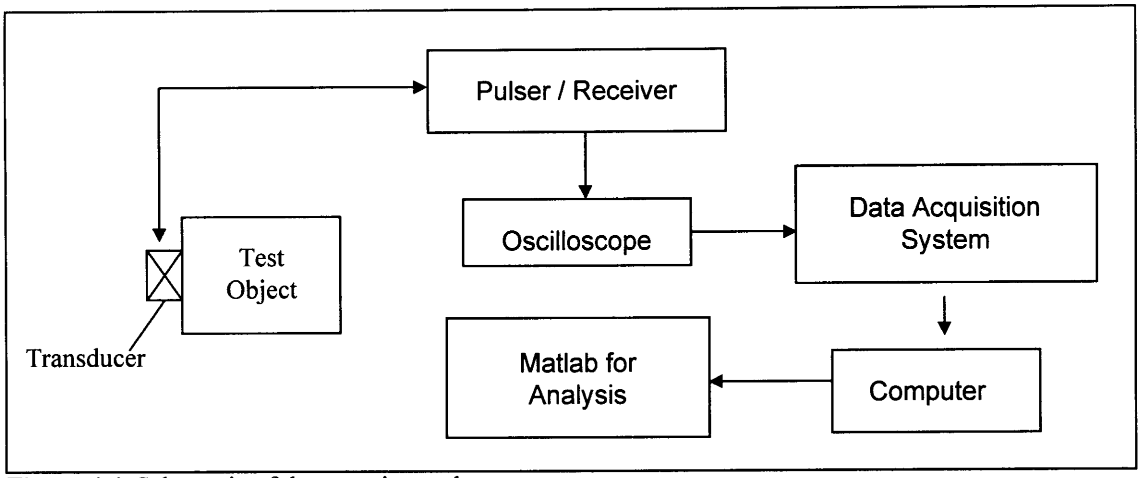

Figure 4.4 Schematic of the epxerimental set-up.

In this study of internal stress levels, a 1" diameter round PVDF film sensor, 28 mm. in thickness, was bonded by silver filled epoxy to wire leads and connected to BNC cables. This produced a working piezofilm transducer. To simulate stresses induced in the transducer if it had been bonded to a dynamically wind loaded envelope seal, the film was subjected to various compressive stresses in form of positive pressures. A clear difference in the voltages emitted by the sensor was noticable when the film was inactive and when it was highly stressed. See figures 4.5 and 4.6 for time domain plots of the signal amplitude data . The order of magnitude of the difference in voltage values was 10. This is very promising. These results indicate that the principle of using PVDF to determine internal stresses in SSG sealant is valid and worthy of further development.

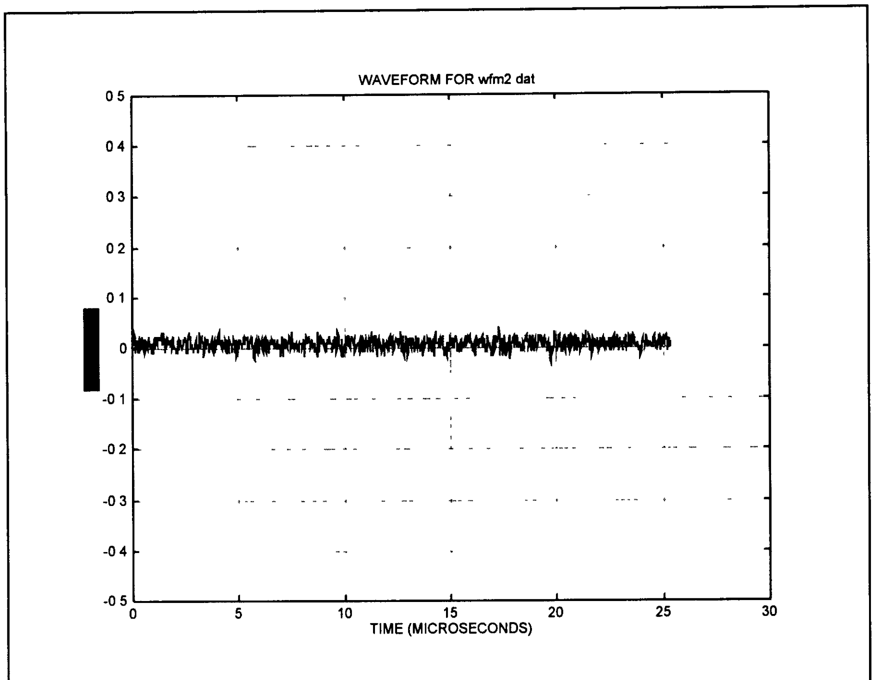

Figure 4.5 Time domain plot of PVDF in an under-stressed condition.

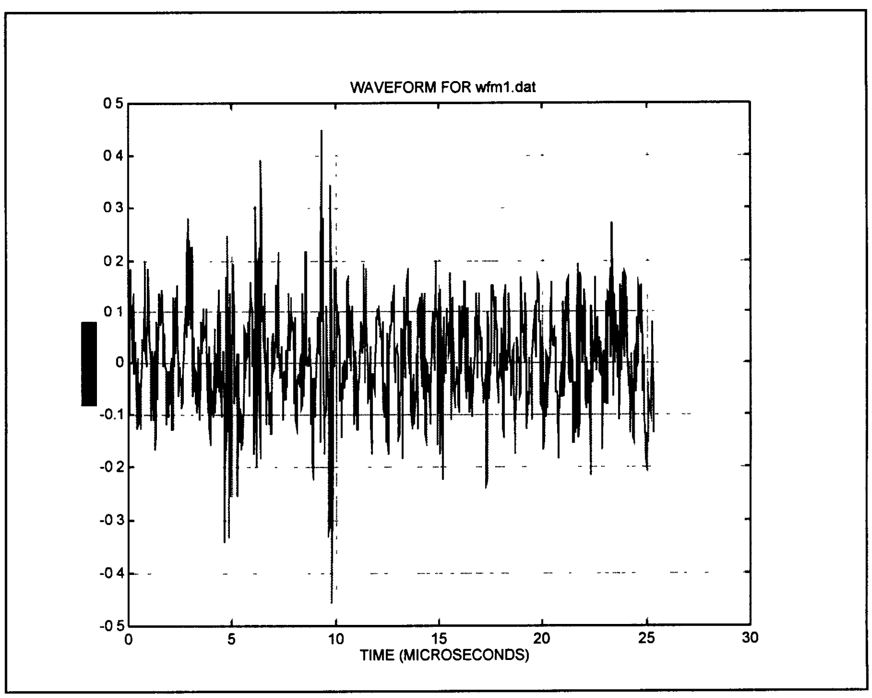

Figure 4.6 Time domain plot of PVDF under stressful conditions.

4.5.2 Suggestions for implementation

The idea of reporting values from local sensors to a building automation system (BAS) has much promise. Data from individual sensors can be channeled to an integrated sensor system. Such a system can be developed to gather information from individual sensors and prepare packets of information regarding stress levels in chosen critical regions of the building envelope. A set-point must be established for the building automation system to be able to reference current voltages readings to and assess whether the value obtained warrants concern.

Setpoints are parameter values programmed into an automation system. If values of the current input exceed the setpoint, it triggers an alarm in the system. Setpoints should be established for key locations in the building automation system. The refernce value for the setpoint should be calculated based on the location and configuration of the seal and PVDF sensor. Once upper limit voltage values corresponding to the maximum design strength of the seal have been established the BAS system will be equipped with tools to trigger alarms at appropriate times.

4.6 Testing Of Structural Silicone Adhesive Bond Integrity

A structural sealant must be strong and flexible enough to accomodate stresses in several directions, then regain its original shape without breaking. Breakage results in lack of adhesion or cohesion. Lack of adhesion may be caused by stresses induced by wind or thermal factors. Lack of adhesion may also be present very early in the life of the structure due to frost or some oil contamination on substrates which was not removed prior to installation. Incompatibility of materials is also a cause of adhesion problems. Lack of adhesion may occur during installation, or the condition may take place sometime during the service life of the envelope system. In any of these cases, the material has a broken or debonded interface where a continuously bonded one should exist.

As mentioned before, in the pulse echo technique description, time of flight of the reflections correspond to material and layer thicknesses. One can identify and calibrate ultrasound reflections of a satisfactorily bonded seal configuration by knowing the proper sealant, glazing, and mullion thicknesses, geometry and orientation. Acoustic properties of the materials of these components must also be known. Bondline thicknesses are usually smaller than the solid material thicknesses, therefore front and back surface reflections of a bondline are normally superimposed one on the other.

Debonding and lack of adhesion can be determined by monitoring back surface and intermediate reflections of a signal as sound travels through the seal and other components of the SSG system's configuration. Where a debonded situation occurs, sound is unable to fully penetrate the bondline of the seal-to-glazing, or the seal-to-mullion interface. Lack of cohesion is also detectable by this same phenomena. A reflection coeffiecient of nearly one occurs. This is because air is a poor transitter of sound and air essentially replaces the intact bondline. Much of the incident sound returns prematurely to the receiving transmitter, see figures 4.7 and 4.8, instead of continuing to propagate through what should be a properly bonded sealant/substrate arrangement. The phenomena results in unanticipated reflections evident in time domian plots of sound pulses propagated through a debonded glass and sealant specimen. Unanticipated reflections indicating major sound reflection at unexpected depths in the tested specimen, and excessive attenuation of the sound pulse reflection off the backwall of the tested specimen due to losses incurred at the debonded interface indicate that material is debonded from its substrate.

4.6.1 Conducted Seal Debonded and Bonded Experiment and Results

This phenomena was also investigated by means of experiments for this thesis. A specimen was prepared to simulate the glass/sealant bond found in SSG systems. Dow 100% silicone sealant was applied to an 3/16 inch glass panel and cured for 3 days. After complete cure (minimum time required 24 hours) a portion of the seal was failed and completely debonded from the glass lite.

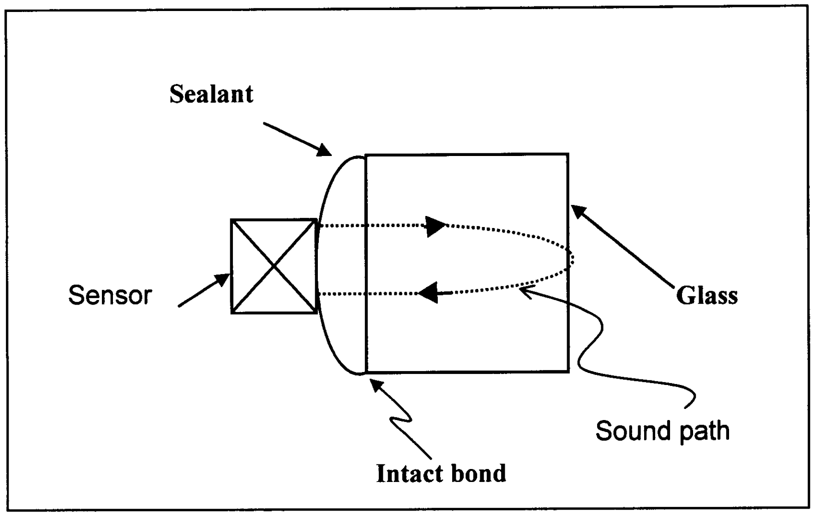

Figure 4.7 Path of sound reflection in a specimen with an intact interface.

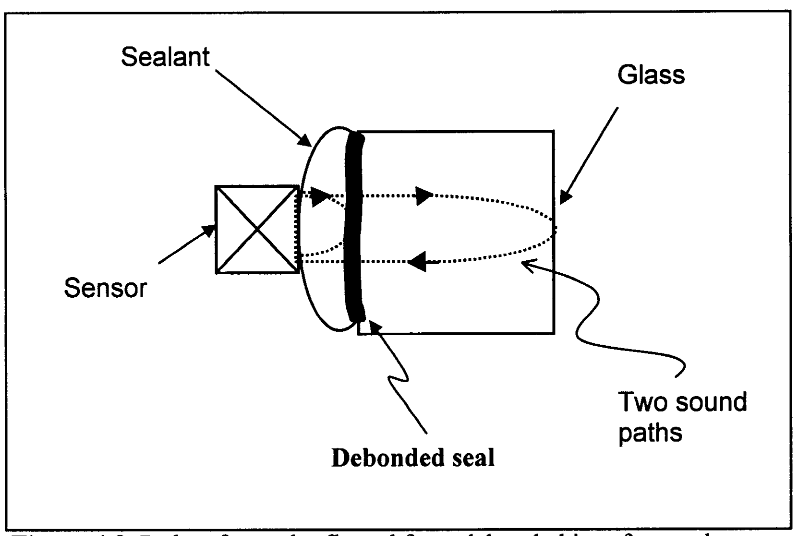

Figure 4.8 Paths of sound reflected from debonded interface and backwall of testing specimen.

Time domain plots from ultrasonic characterization tests of the bonded and debonded configurations are shown in Figures 4.9 and 4.10.

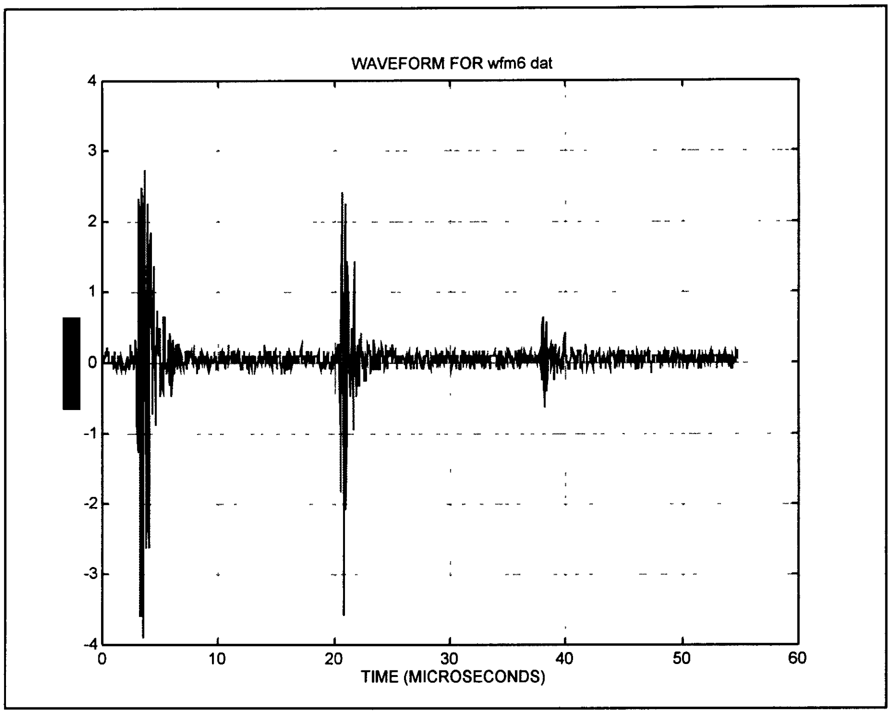

Figure 4.9 Reflections through a properly bonded sealant/glass specimen.

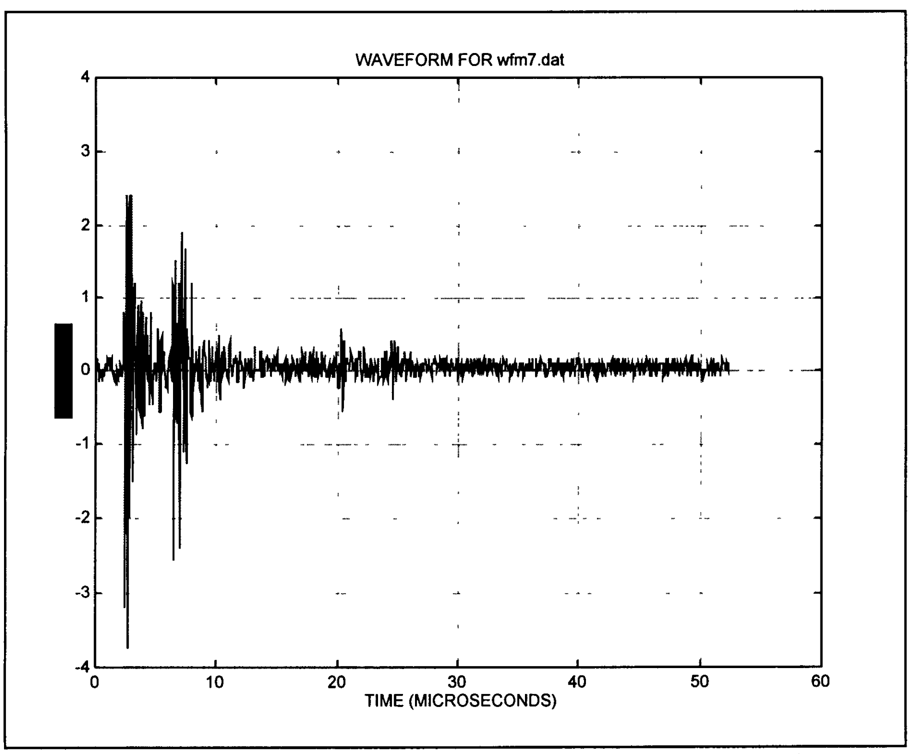

Figure 4.10 Signal from ultrasonic tests of a debonded sealant/glass specimen.

4.6.2 Interpretation of Experimental Results

Time domain plots of ultrasonic tests conducted on bonded and debonded test specimens are shown in figures 4.9 and 4.10. Observe both plots and note differences in time-of-flight data between reflections or echoes, material thicknesses of the test specimens, orientation of the transducer, and wavespeed through the specimen materials. Differences in properties of the signals and specimens enables one to determine the existence and depth of a debonded bond. Also, note the difference in times at which reflections occur in the two plots. The intermediate reflections which exist in the figure 4.10 as compared to figure 4.9, and the extreme attenuation of the backwall echoes in figure 4.10 all indicate debonded bondlines. Signifcant and useful information can be extracted from the presence or absence of echo pulses.

Figure 4.9, the time domain plot of the satisfactorily bonded seal/glass configuration, shows the incident pulse and two echoes with time of flights that correspond to sound that traversed the specimen a distance twice its entire thickness virtually uninterrupted. See figure 4.7 for a schematic of the described sound path. Acoustic properties of the silicone seal and glass are listed in Table 4.1.

Table 4.1 Acoustic Properties of Silicone Glazing System Materials

Material	Density (ρ) g/cm^3	Longitudinal Velocity km/s	Impedence(Z) 10^6 Rayl
Silicone Rubber	1.05	1.03	1.1
Glass	2.24	5.64	12.6
Aluminum	2.7	6.35	17.1

Although the glass and sealant have completely different acoustic properties, the echos in the signal correspond to reflections from the backwall of the entire configuration only. No other discontinuity was detected. This information is confirmed by time-of-flight information retrieved from the signal and material soundspeed. Acoustic properties of silicone seal material and glass are listed in Table 4.1. Time-of-flight (TOF) values measured from the echo are 17.3 μs (microseconds). If the bondline was not perfect and had contained detectable discontinuities, a TOF value of approximately 13μs would be expected from the first echo. This value corresponds to roundtrip travel through the seal alone. Since the actual measured TOF is 17.3 μs, this indicates the sound travelled undisturbed through the seal and glazing interface; the bondline was perfect and sound energy penetrated with practically no resistance through the interface. Incidentally, the TOF is slightly larger than a value calculated based on thicknesses of the seal and glass alone. The extra time is attributed to additional time needed to travel through coupling material and the bondline interface. Although the bondline interface is not represented in form of a reflection, it should still be accounted for when calculating TOF. Bondline interface material is actually a hybrid of the two contacting materials having unknown thickness. An accurate time-of-flight could not be calculated for this part of the test specimen.

Attenuation did occur in the plot of Figure 4.9, perhaps from scattering or other mechanisms. This phenomena will be discussed more in the section on diffuse discontinuities. Attenuation, α, is expressed in terms of intensity of sound after traversing a distance X through the material [4]:

$$I = I_O \exp(-\alpha X) \qquad [4.1]$$

where:

I_O = initial intensity

α = attenuation in dB/unit length

X = distance travelled through material.

Visually, attenuation can be discerned by looking at time domain plots. Decreases in amplitude or intensity of the echoes of the signal indicate attenuation. Attenuation from Echo1 to Echo2 of Figure 4.9 is insignificant, α = 0.22 dB/inch. However, the value from Echo2 to Echo3 is α = 2.36 dB/inch.

Figure 4.10, time domain plot of the debonded seal/glass specimen, illustrates why this thesis proposes ultrasound as a viable means of detecting debonding in building envelope components. Recall that the time-of-flight for sound to travel through the satisfactorily bonded seal/glass test specimen was 17μs, see figure 4.9. Now, refer to figure 4.10. It is clear that the debonding of seal from glass is strongly detected and illustrated in the signal by the appearance of an intermediate reflection between the initial pulse and backwall echo.

Notice the high intensity energy reflected 4.1μs after entering the seal configuration. The air pocket in between the seal and glass caused by the damaged bondline is not conducive to sound travel and reflects much of the energy back to the receiving transducer. The energy that does penetrate the delamination is reflected off the backwall 17.3 μs after incidence, that corresponds to the value of time needed for reflection of the pulse off the entire configuration's backwall. However, the intensity of the first backwall echo, Echo3, is significantly lower than that of the intact bond's own Echo2, in the Figure 4.9 signal. Attenuation in the debonded case evaluates to be 2.65 dB/inch, where attenuation for the properly bonded echo evaluates only 0.23 dB/inch. In summary, the debonded condition was detectable from the strong intermediate reflection caused by the air pocket formed at the disrupted interface. It was also detectable by the highly attenuated backwall reflection indicating major energy dissipation internal to the specimen.

Implementation of this idea in actual building systems may be done similar to the approach taken in the stress level assessment configuration. Setpoints for attenuation of signals may be established. However, detection of the depth of a debonded region may only be ascertained my looking at time domain data. In this case, time domain information should be made accessible through the BAS for purposes of thickness measurements of bonded layers of a sealant/glass area of the building envelope system.

4.7 Testing of Diffuse Discontinuities In Structural Silicone Sealant

Producers of silicone sealant claim it is highly durable and not prone to many of the issues other sealant materials are afflicted by. However, given the fact that silicone sealant is still a fairly new material (30 years old), it may be suseptible to unforeseen failures as building systems utilizing it age during their service life. Some issues affecting sealants of older structures include crazing, fatigue, hardening, reversion, and bubbling. These issues are discussed briefly in the following two paragraphs. See Figure 4.11 for a schematic of sealant subjected to poor material integrity.

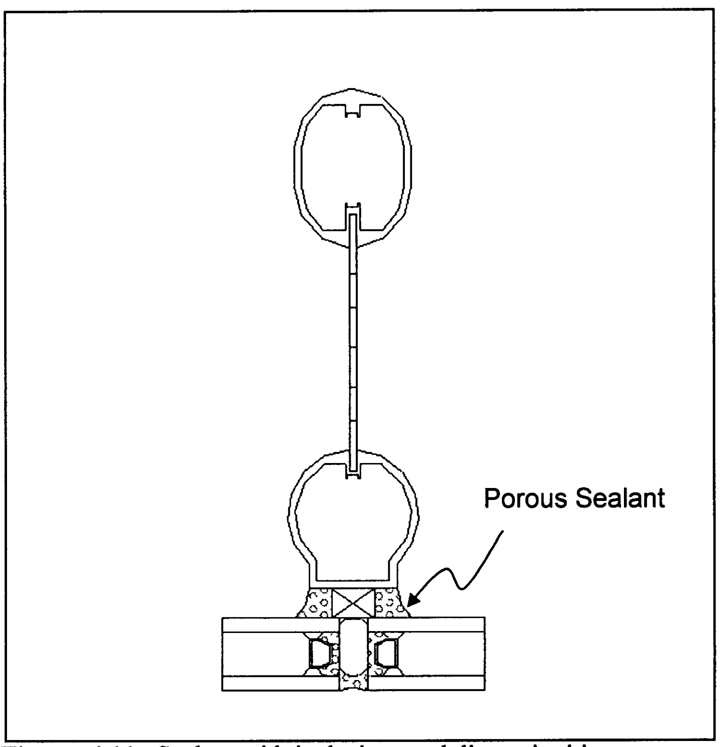

Figure 4.11 Sealant with inclusions and discontinuities

Crazing, or alligatoring, is an inevitable weather-induced deterioration of sealants and is characterized by small, random, surface cracks which resemble surface cracks.

Silicones are not generally prone to crazing. Nevertheless, the material may deteriorate in a similar fashion due to some other cause. Fatigue, repeated cycles of joint opening and closing, is a dominant process in the deterioration of sealants. It is a significant mechanism in premature deterioration leading to both adhesive and cohesive failures. Some sealants increase in modulus of elasticity and hardness as they weather, resulting in a loss of elasticity in certain regions of the seal. This could also lead to adhesive or cohesive failure.

Silicones gradually increase in hardness. If hardening occurs disproportionately in the material, stress concentrations could develop while in service. Reversion is the loss of elastomeric property of a cured sealant which sometimes appears melted or gummy. After reversion, the sealant is no longer a cured rubber and may take on new shapes. Finally, ruptured bubbles in the surface of a sealant can destroy its integrity. Bubbling is usually caused by gas escaping from the sealant, backer of the sealant, or substrate.

All of the aforementioned issues affect a sealant's composition, microstructure, and morphology. Mechanical properties are affected by these material characteristics. Ultrasonics are a valid way of assessing these material characteristics because these factors also influence ultrasonic wave propagation. Correlations between ultrasonic wave parameters and material variables allow for prediction of strength, hardness, toughness, and other properties.

Nondestructive material characterization may be used when the presence, identity, and distribution of minute discontinuities in a material can only be assessed statistically [4]. This thesis proposes ultrasonic methods as a means for evaluating dispersed discontinuities in structural silicone sealant. In sealant, discontinuities may be so microscopic and numerous that it would be impractical to resolve them individually. However, evaluation of peculiarities in the seal are necessary, because they yield rich information regarding capabilities of the component. High numbers of discontinuities produce degraded bulk mechanical properties and strength deficiencies. Even if a structure is free from a single large, critical discontinuity, it may still be susceptible to failure because of inadequate or degraded mechanical properties.

Changes in wave propagation speed and energy losses from interactions with material microstructure are two key factors in ultrasonic determination of material properties. Variations of velocity and attenuation are associated with significant variations in microstructural characteristics and mechanical properties.

4.7.1 Results of the Conducted Diffuse Discontinuity Experiment

Another experiment was conducted for this thesis as a means of validating another application of the ultrasonic testing method. In this case, efficiency of ultrasonic methods for testing diffuse discontinuities in silicone sealant was investigated. Two 100% silicone rubber specimens were produced. Small diffuse discontiuities were simulated in one of the test specimens by (1) agitating the uncured sealant by rapidly stirring it to produce bubbles or porosity within, and (2) folding sand particulates in the already porous, uncured selant. The uncured sealant was so viscous that the air remained trapped in the specimen directly through the curing process. A control was made by simply preparing and curing sealant under strict control so as not to produce any discontinuities in the material. The specimens were cut to relatively equal thicknesses of 0.15". The pulse echo technique was used to insonify the test objects and collect sound energy records. Refer to figures 4.12 and 4.13 for sketches of the testing setup for this experiment.

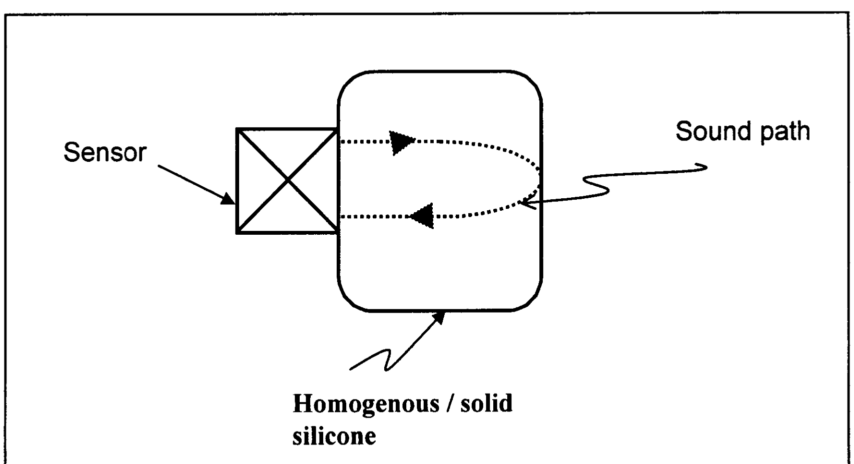

Figure 4.12 Sound path through a homogeneous silcione specimen.

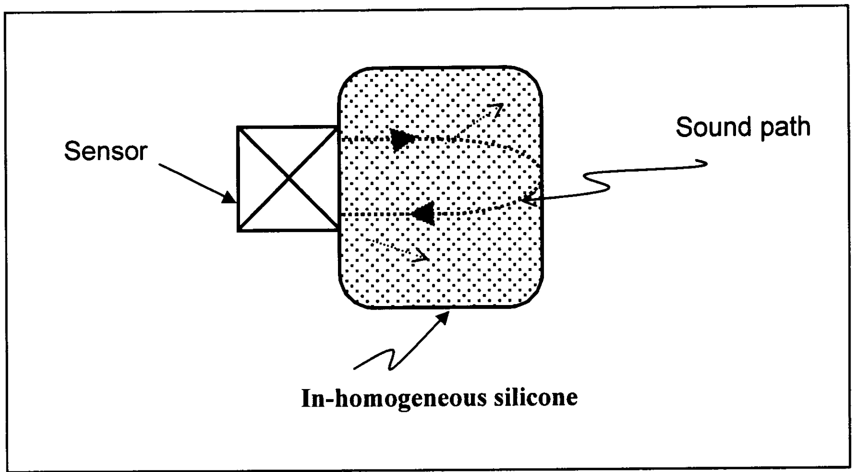

Figure 4.13 Scattered sound path through an in-homogeneous silcione specimen.

4.7.2 Interpretation of Experimental Results

As expected, time domain plots of the ultrasonic tests of the specimens with and without diffuse discontinuities show significant differences. See figures 4.14 and 4.15 for time domain plots.

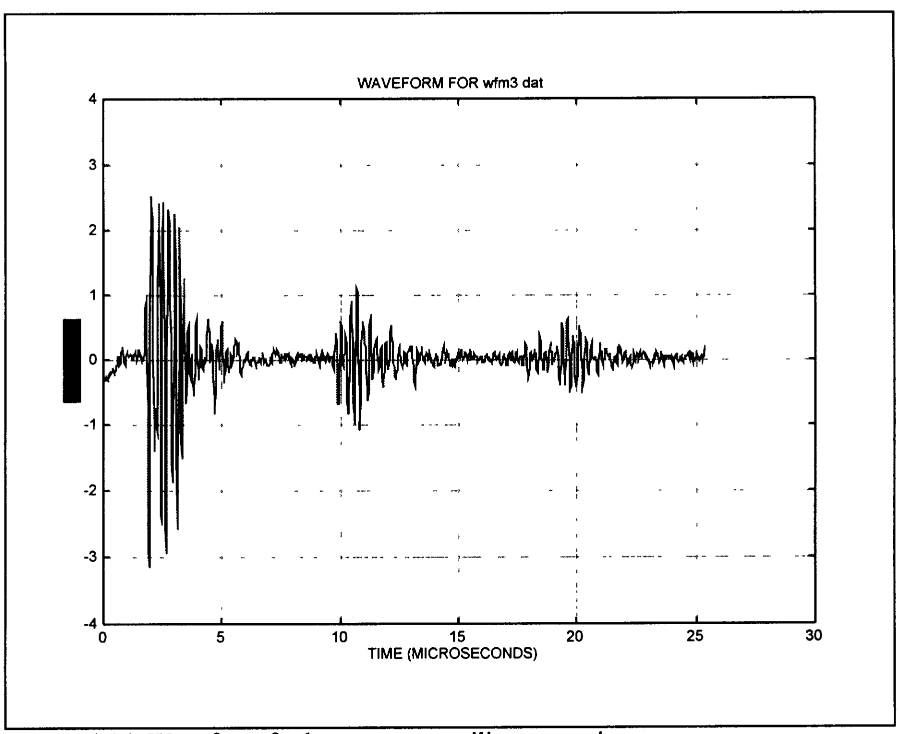

Figure 4.14 Waveform for homogeneous silicone specimen.

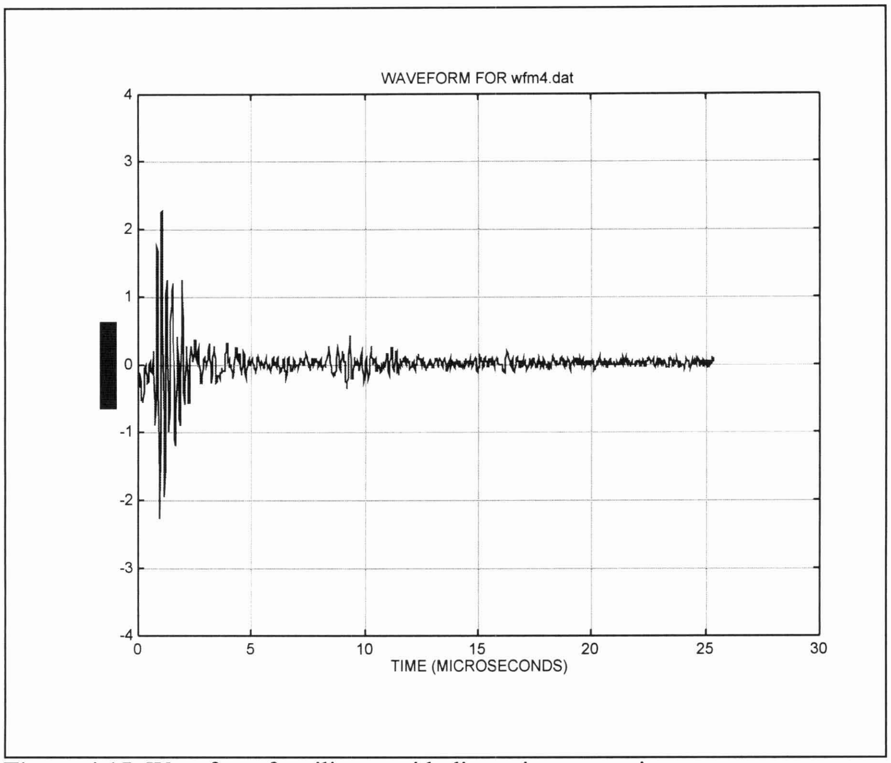

Figure 4.15 Waveform for silicone with dispersive properties.

Cutting and preparation of the specimens caused some surface roughness which resulted in noticeable noise in the signals. The noise is negligible and insignificant when considering the results that prove ultrasound's ability to detect dispersed discontinuities. Attenutation is the only wave property addressed here. Both echos in Figure 4.14 , a time domain plot of the testing data from the homogeneous sample, have α = ~2.75 dB/inch. This seems somewhat high, but that attenuation is attributable to surface roughness, not internal discontinuities. Sealants don't generally have such high surface roughness when installed in the field; however, resources where not optimal to reproduce exact field conditions. Figure 4.15, the plot of data from the dispersive material exhibits only one echo which was significantly attenuated. Attenuation under this condition was 5.36 dB/inch. Clearly, the ultrasound was able to identify the highly dispersive nature of the material. Seals undergoing material deterioration would be identifiable through these means.

For actual implementation of this idea, attenuation values may be reported to some central data bank that has setpoints established for acceptable intensities of pulsed wave energy traveling through the seal. If intensity values are lower than the setpoint and indicate high attenuation in the absence of a debonded or some other critical situation, poor material microstructure may be contemplated as a source of the problem. Figure 4.15 illustrates so much diffision of energy that multiple reflections were unable to appear. In actual building envelope conditions, such degradation of a seal should not be given opportunity to occur.

4.8 Nondestructive Evaluation Summary

Analyzers of ultrasonic data produced from these suggested SSG system seal evaluation methods have two tools to use for troubleshooting component integrity. They can use attenuation values as an indicator of potential problems in the material. Thereafter, they can examine time of flight values to assess depths of expected and unexpected reflections or echos. This resolves location of major debonding or problematic interfacial issues.

CHAPTER 5

RECOMMENDATIONS FOR A SMART CLADDING SYSTEM

5.1 Material, Components, and Construction of a Smart Glass Cladding System

Guidelines and considerations for construction of a traditional structural glazing system are well established by the American Architectural Manufacturers Association (AAMA). Rigorous procedures and standards have been established for the glass, metal frame, and sealants. Glass types, clearances, maximum loads and stresses, coatings and finishes, structural requirements, backing and spacers, and performance tests are among the considerations addressed in the design guidelines prescribed in the booklet "Structural Sealant Glazing Systems (A Design Guide): AAMA Aluminum Curtain Wall Series". [3]

5.2 A Multiple Sensor Surveillance System for Smart Cladding

Besides development of a reliable and cost effective PVDF sensor, strategic location of sensors in the monitoring system is probably the most challenging aspect of developing the diagnostics program. The PVDF sensors would serve very localized areas. Condition assessment of the entire cladding in question requires a significant number of sensors located at crucial regions in the structure. A suggested instrumentation scheme is a multiple sensor surveillance system that places PVDF sensors @ 1'0" as a trial spacing on sealant around the periphery of each glazing panel. Such an instrumentation scheme value should be tested experimentally for reasonable results. See Figure 5.1 for a rough sketch of the instrumentation scheme.

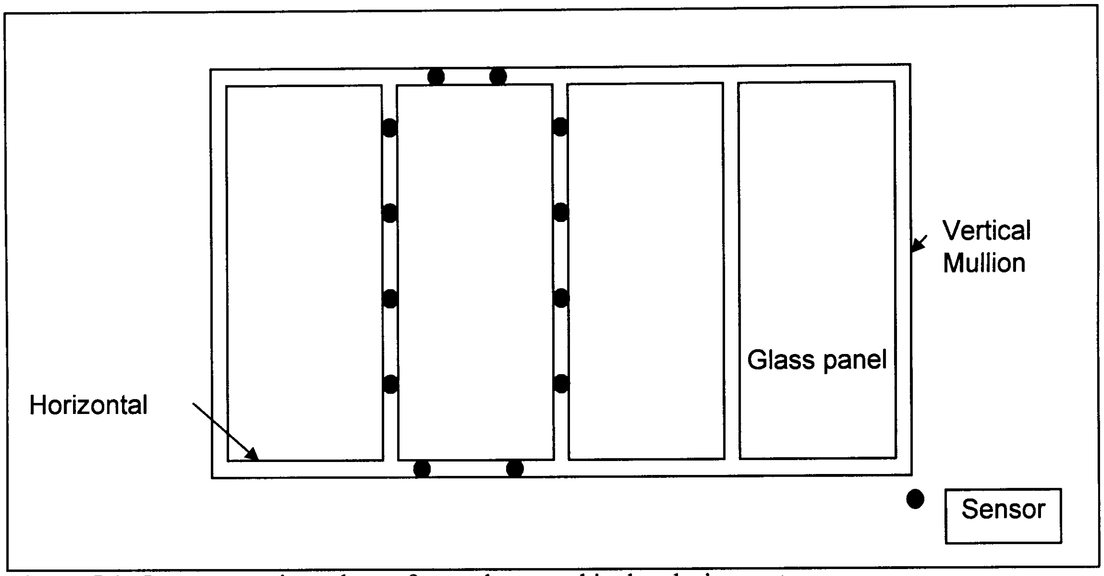

Figure 5.1. Instrumentation scheme for a select panel in the glazing system.

Central level and sensor level tracking capability is desirable for comprehensive assessment of the cladding condition. Sensor level tracking may provide information at a specific location in the wall which may be problematic. Central level tracking should be used to compile information on regions within the cladding system. Design of the data processing programs should be tailored to yield status reports from any combination of sensors in the system. See Figure 5.2 for a schematic of the combined sensor and central level tracking approach.

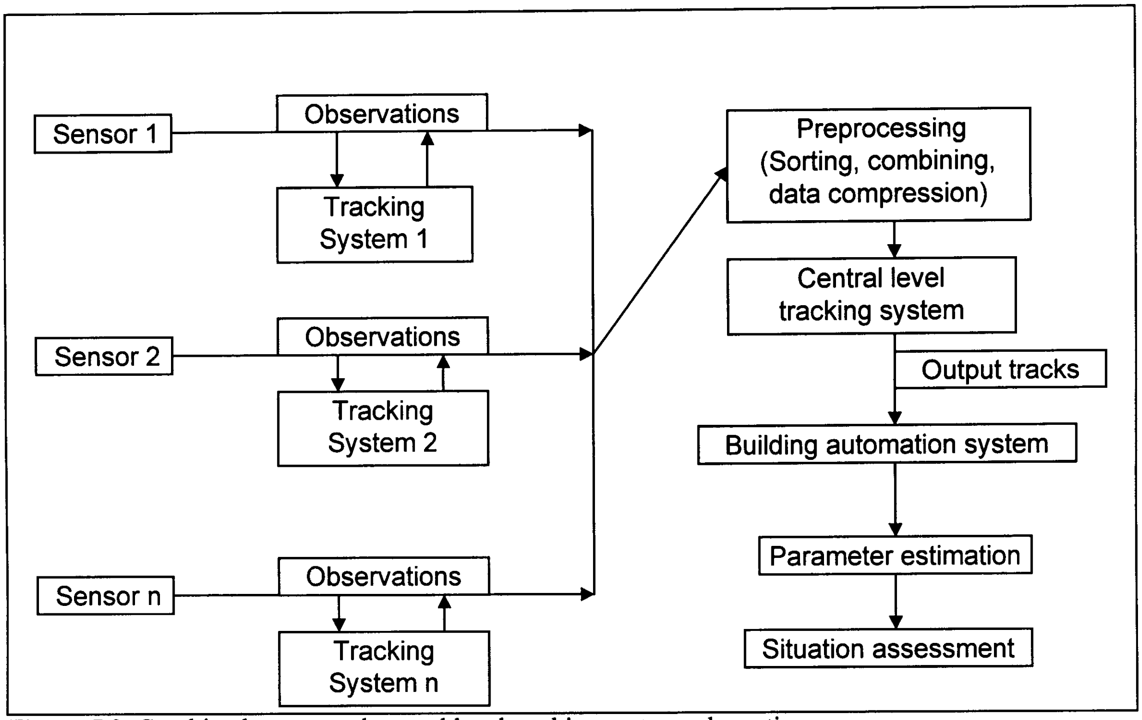

Figure 5.2 Combined sensor and central level tracking system schematic.

5.3 Constructing a Smart Cladding System

Key components of the smart cladding system have been discussed. They include principal frame members, structural glazing materials, and sensors. However, there are many more constituents of a truly smart cladding system. A multi-sensor surveillance system with the major components discussed also relies on sophisticated cable and wiring, communication buses, acquisition systems, central and management level computers (which may be part of the Building Automation System), data acquisition systems, monitoring programs and maintenance management programs. Besides the physical attributes of the system, planning, installation procedures, training, and construction support must all be established. It is an exciting, yet challenging task. Nevertheless, long term benefits make the investment one to consider, for example: energy efficiency, optimization of construction materials, financial savings, and extended lifetime of the facility.

Since it is evident that a potential nondestructive technique for evaluation of structural silicone sealants exists, discussion of incorporating such a feature into actual buildings is due. Development of such systems requires many resources: additional sensors, extra processes to transform raw data into useful data, and extra time to mangage the systems[7]. Cost-effectiveness of such investments are not always proven. However, in this particular case, savings from reduced structural and cosmetic replacements, reduced indoor air quality problems, and energy efficiency more than justify incorporation of an SSG system seal evaluation program.

Ideally, a building automation system (BAS) will measure many environmental factors on the status of the building and in effect identify when repairs are needed. This thesis proposes adding another feature to BASs which outfits them with measurements systems for assessing of degradation in the building's envelope structure. This is essentially a diagnostic or surveillance system.

5.4 A Modified Building Automation System

Building automation systems centralize operation, monitoring, and management of building systems, such as heating, ventilating, air-conditioning (HVAC), lighting, fire safety, and security access. The goal of these systems is to provide a comfortable and healthy environment for building occupants, reduce energy costs, and maintain a high level of life and fire safety. These systems allow building owners and facility managers to operate their facilities more efficiently and optimize productivity of operations personel.[8]

Initially, BASs were primarily electro-mechanical with sensors and controlled devices that were hardwired or piped to a large central control panel. Current systems are highly computerized. Today's systems consist of remote sensors and actuators, micro-processor based controllers, optional central host computers (normally PCs) and an optional mangement host computer. See Figure 5.3 for a schematic.

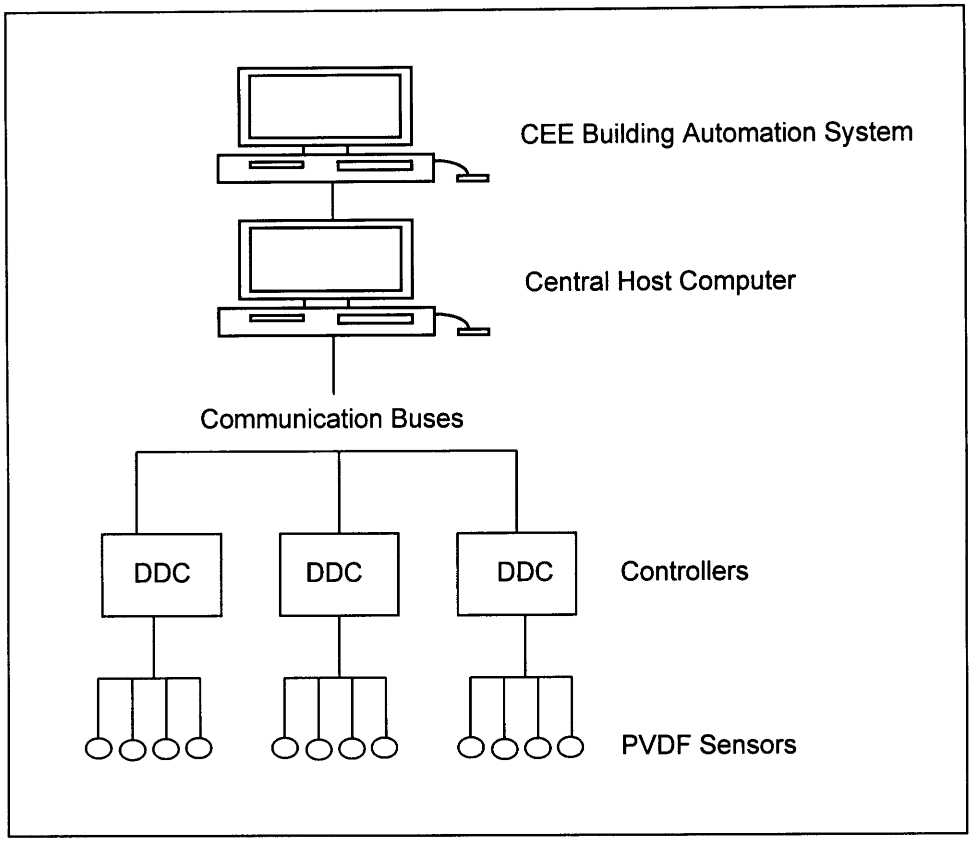

Figure 5.3 Proposed monitoring system architecture.

The remote sensors sample building environment data and transmit it to the controllers. The controllers perform control functions and energy management strategies by controlling remote actuation devices. Building management reporting, monitoring, and access to system data can be accomplished through the controllers, the central host, and host computers. This proposal assumes it is quite feasible to have this same system infrastructure collect, transmit, and compile data from the smart cladding system devices and components to yield situation assessment of the skin.

The sensors, actuators, and controlled devices that are connected to controllers are known as points. Points are classified by their input or output functions: digital inputs or outputs (DI or DO) , and analog inputs or output (AI or AO). The PVDF sensors serve as analog inputs. Analog inputs are devices that send a proportional or variable signal to the controller. Unlike digital input devices, analog input signals are sent over the entire range of the sensing device. Most controllers will accepts analog input signals of 2 to 10 volts

DC, 4 to 20 milliAmp, or a variable resistance. PVDF sensors should be able to meet these standards. Pre-amplification or pre-damping may be incorporated if needs be.

In general, controllers receive signals from sensors, compare the signal with a preset setpoint, and determine if corrective action is necessary. Corrective action is in the form of an output signal to modulate an actuator or controlled device. In the case of the smart cladding system, the corrective action may be an alarm sounded to pertinent people in the CEE department or MIT physical plant headquarters.

Controllers' software programs are in digital form and perform direct digital control. Microprocessor-based controllers can be used alone or incorporated in the BAS. In the case of the sealant diagnostics signals, it is best the data be reported directly to the BAS. Microprocessor –based controllers are ideal for the proposed system because they allow revisions to control sequences without major hardware changes, simply by changing the software. These controllers are easily maintained, reliable, and often include self-diagnostic features to notify maintenance personnel of any malfunctions.

Communication buses link controllers to one another as well as to the central host computer. The most common bus media in current BAS are twisted shielded copper hard wire, direct-dial telephone lines, and fiber optic cable. Factors affecting selection of the type of medium are cost, geographical layout, and possibilty of electronic interference. For applications of smart cladding, installation of the media are a key issue. The media selected must not be obviously detectable of the building skin. Particularly in the glazing. The solution to this problen may be to select fiber optic cables which have high capacity, but are very small and able to be disguised. Fiber optic communication buses are particularly well-suited in an environment that interferes with its communications, like areas subject to radio frequencies generated by electrical power lines or elctrical storms. This is a bonus since location of these cables on the glazed building skin don't aesthetically allow for robust rubber insulation. The disadvantages of fiber optic transmission are high material and installation costs and absence of established guidlelines for this technology. Acutally, undertaking this proposal may be quite costly initially due to the nonexistence of previous related work.

The central host and management host computers act as operator-machine interfaces. They provide the operator with a way to access program information, point information, and management reports. They also allow the operator to monitor equipment status, receive alarms, and take corrective action when alarms occur. These computers possess all the devices that powerful personal computers possess, including peripheral devices. Management functions and duties fulfilled by these computers include [8]:

- Transfer of operator authority and assignments during regular or unattended periods of building operation.
- Logging and reporting of any changes to the BAS programs identified by operators.
- Reports and summaries of all alarms and facility management information.
- Archiving of all controller software packages.
- Operator and maintenance means to oversee, and fine tune a facilities most critical systems on adyanmics basis.
- Segregated alarms pertaining to a facilities most critical systems.

5.5 Potential Cost for A Smart Cladding System

The concept proposed in this thesis is completely unprecedented. As such, it is a challenging feat to produce an accurate cost estimate for such a system. Preliminary cost estimates for the sensor system alone excluding the glazing system suggested a cost of approximately $60.00 for instrumentation for a - 8' x 15' standard single pane glass lite or panel. This value includes all items associated with establishment of the diagnostics system as best can be predicted this early in development stages of the design concept.
The cost of an actual structural sealant glazing system depends on the fabricator of the system because the industry is currently very specialized and specific to the particular system selected. Very rough estimates for an SSG curtain wall system are in the area of about $27.00 per square foot in 1998. Again, these numbers are somewhat random, because actual figures depend on the building, manufacturer, and materials in question.

Table 5.1. Rough Cost Estimates for a smart cladding system.

Accessory	Crew	Daily Output	Man-Hour	Unit	Mat Cost	Labor Cost	Equip	Sub-	Total O&P
SSG Curtain Wall	H-1	160	.200	S.F.	20.00	5.15		25.15	27.00
PVDF System/Panel	1 Elec.			Panel	30	25.00		55.5	60.00
Microprocessor Controllers	1 Elec.			Each					250
Communication Buses				C.L.F					850
Central Host Computer									NA
Management Host Computer									NA

The author's contention is that once the idea has been thoroughly researched and tested, the price should reduce significantly. Such is the case with most high-tech new ventures. Venture capital will always represent the highest cost ever associated with the projects.

CHAPTER 6

CONCLUSION

Building integrity is highly dependent on decisions concerning component materials, design, and standards. The integration of structure and maintenance is critical to the structure's strength, stability, and performance. The integration is also important for ensuring safety, comfort, health, efficiency, and appearance through seasonal thermal expansion and contraction cycles, through changes in dead and live loads, and in the face of natural disasters.

High performance criteria for a building include energy and resource conservation, functional appropriateness, strength and stability, durability, safety, weathertightness, visual comfort, and economic efficacy. The notion of performance in buildings is increasingly being addressed. It is those issues that have prompted the proposal of a high performance cladding system. Responsible and sustainable engineering demands unusually good building integrity against degradation in appearance, in structural integrity, and environmental properties. In order to address these performance mandates, current designers must establish responsible priorities.

New materials currently prompt innovative design approaches to aesthetics and usablity. Structural Silicone Glazing Systems are a product of innovative uses of newer materials. However, along with advancement of materials, should come advancement of performance. A high performance glazed building envelope system with diagnostic capabilities provides an opportunity for features ranging from material conservation to energy conservation. This seems like the perfect complement to aesthetically pleasing glazed envelopes.

Envelope systems with nondestructive capabilities are just a beginning to establishing structures that will be utilized to their fullest potential through comprehensive design procedures and proper maintenance programs.

APPENDIX

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